



UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

Escola Tècnica Superior d'Enginyeria
Industrial de Barcelona

Calibration of gamma radiation beams of a secondary standards dosimetry laboratory: Programme Feixos19

Master's thesis

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Author: Daniel Costa Vargas

Director: Dr. Mercè Ginjaume Egidio

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Resum

En aquest projecte s'elabora un nou software informàtic, anomenat Feixos19, que permet definir les condicions experimentals per calibrar monitors de protecció radiològica amb feixos gamma en el laboratori de calibratge i dosimetria del Institut de Tècniques Energètiques (INTE) de la UPC. En aquesta memòria s'introdueix primerament la metrologia, especialment la metrologia per a radiacions ionitzants, aplicant conceptes bàsics de la dosimetria i la protecció radiològica. Més endavant, el projecte descriu el laboratori de calibratge i dosimetria del INTE, com exemple de laboratori de calibratge, i com aquest laboratori calibra els monitors de protecció radiològica amb feixos gamma. Seguidament, s'explica com es calibren els feixos gamma i s'exposa un exemple pràctic. Finalment es descriu la base, el posterior desenvolupament i la conseqüent elaboració del programa Feixos19.

Abstract

In this project, a new software called “Feixos19” is developed to allow defining the experimental conditions to calibrate protection monitors or to irradiate passive dosimeters with gamma beams in the calibration and dosimetry laboratory of the “Institut de Tècniques Energètiques” (INTE) of UPC. At the beginning of this project, the metrology, especially metrology for ionizing radiation, is introduced with basic concepts of dosimetry and radiation protection. More ahead, this project describes the calibration and dosimetry laboratory of the INTE, as an example of a calibration laboratory, and how this laboratory calibrates the radiation protection monitors with gamma beams. Next, it is explained how to calibrate gamma beams with a practical example. Finally, it is described the basis, the subsequent development and the consequent elaboration of “Feixos19”.

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Contents

1. INTRODUCTION	8
1.1. Background	8
1.2. Aim.....	9
2. METROLOGY	10
2.1. Calibration laboratories	11
2.1.1. Reference ISO 4037 standard	11
3. QUANTITIES AND UNITS OF RADIATION PROTECTION	13
3.1. Protection quantities	13
3.1.1. Equivalent dose and radiation weighting factors	13
3.1.2. Effective dose and tissue weighting factors	14
3.2. Operational dose quantities	15
3.2.1. Operation quantities for area monitoring	16
3.2.2. Operation quantities for individual monitoring	18
3.2.3. Reference quantity.....	21
4. SECONDARY STANDARD CALIBRATION LABORATORY (LABORATORI DE CALIBRATGE I DOSIMETRIA LCD) AT THE INSTITUT DE TÈCNiques ENERGETIQUES	23
4.1. Introduction	23
4.2. The photon irradiation room	24
4.2.1. Photon calibration laboratory	24
4.2.2. Gamma irradiator	25
4.2.3. Radioactive sources.....	26
4.2.4. Calibration bench	27
4.2.5. Safe and control system	28
4.2.6. Reference detection system. Standard chambers	29
4.2.7. Auxiliary equipment for atmospheric conditions	31
5. DETERMINATION OF THE PHOTON BEAMS EQUATIONS	32
5.1. Introduction	32
5.2. Measurements.....	32

5.3.	Calculation.....	33
5.4.	Results	36
6.	FEIXOS99	38
6.1.	Introduction	38
6.2.	Black box description.....	38
6.3.	Feixos99 code.....	40
6.3.1.	Input section	40
6.3.2.	REM subroutine	41
6.3.3.	Parameters loading 1	41
6.3.4.	Air kerma range.....	41
6.3.5.	Parameters loading 2	42
6.3.6.	Calculation algorithm.....	42
6.3.7.	Result.....	43
6.4.	Taxa99	43
6.5.	Improvements in the new version of Feixos99	44
7.	FEIXOS19	45
7.1.	Introduction	45
7.2.	The new black box	45
7.3.	Feixos19 code.....	47
7.3.1.	“Feixos”	47
7.3.2.	“Dades”	49
7.3.3.	“Llistes”	50
7.3.4.	“Càlcul”	50
7.3.5.	The new algorithm method	51
7.3.6.	Macro “Ejecutar_calculo”	53
8.	DEBUGGING AND VERIFICATION OF “FEIXOS19”	56
8.1.	Debugging and verification conditions	56
8.1.1.	Free variable	56
8.2.	Conditions	57

8.2.1.	Verification of the beam equations	57
8.2.2.	Verification of the conversion factor	58
8.2.3.	Influence of tissue thickness	59
8.2.4.	Influence of ambient conditions.....	59
8.2.5.	Influence of date.....	59
8.2.6.	Verification of bench distance	60
8.2.7.	Verification of “integrate” mode.....	60
8.3.	Results	61
9.	CONCLUSIONS	62
10.	BIBLIOGRAPHY	63

Appendixes

- Appendix 1. Layout of NI-641
- Appendix 2. Scheme of NI-641
- Appendix 3. Calibration certificate PTW TM32002
- Appendix 4. Calibration certificate LS-10
- Appendix 5. “Informe de calibración interna haz nº2”
- Appendix 6. Data collection sheet of calibration
- Appendix 7. Code of Feixos99
- Appendix 8. Code of Feixos19
- Appendix 9. Results of validation process

1. Introduction

1.1. Background

Radioactivity is a natural phenomenon and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation risks to workers and the public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled. Activities such as the medical uses of radiation, the operation of nuclear installations, the production, transport and use of radioactive material, and the management of radioactive waste must therefore be subject to standards of safety. (IAEA, 2014)

Environmental monitoring around workplaces using ionizing radiation, and individual monitoring of workers exposed to external ionizing radiation is essential to ensure a good protection. In Europe, the EURATOM Directive 2013/59 (EC, 2019) establishes uniform basic safety standards for the protection of the health of individuals subject to occupational, medical and public exposures against the dangers arising from ionizing radiation. Such safety standard is based on ICRP discussed recommendation by experts in RP (Radiation Protection) field. EURATOM Directive applies to any planned, existing or emergency exposure situation which involves a risk from exposure to ionizing radiation which cannot be disregarded from a radiation protection point of view or with regards to the environment in view of long-term human health protection.

Among others, it establishes requirements for workers and workplaces monitoring, the definition of quantities of interest to assess radiation risk and dose limits to prevent unacceptable risks.

Radiation monitoring is performed using appropriate detectors which are sensible to radiation and can assess the presence of radiation providing a quantitative value. International Organizations such as the IAEA or the ISO (4037-1 + 4037-3) provide guidance to establish and operate calibration facilities for radiation monitoring instruments: reference sources of radiation, standard instruments and calibration techniques.

The Secondary Standard Calibration Laboratory (LCD) at the Institut de Tècniques Energètiques (INTE) of the Universitat Politècnica de Catalunya is a calibration Laboratory for ionizing radiation accredited by the Spanish National Accreditation Body (ENAC) based on the ISO 17025 Standard (UNE-EN, 2017). The LCD obtained its first formal recognition in 1987 in compliance with the EN 45001 (EN, 1989) standard and since 2009 according to the ISO/IEC 17025. In the following paragraphs, an introduction about metrology and radiation protection quantities is presented.

1.2. Aim

The goal of this project is to develop a software programme that allows defining the experimental conditions to calibrate radiation protection monitors or to irradiate passive dosimeters with gamma beams in the Secondary Standard Calibration Laboratory (LCD) at the Institut de Tècniques Energètiques (INTE) of the Universitat Politècnica de Catalunya (UPC). More specifically, it aims at designing and writing a new programme that will improve the programme that has been used at the LCD since 1999.

The former programme was written in DOS-Basic and at present it is difficult to compile it and to integrate it to the rest of the management system in place at the LCD. The new proposal will be based on an excel programme.

2. Metrology

Metrology is the science of measurement. It includes both theoretical and practical aspects of measurements, its uncertainties' calculations and its application. Basically, national laboratories and accredited laboratories, where calibrations of instruments are performed, are laboratories of metrology. (Centro Español de Metrología, 2012)

A calibration is defined as the comparison of the response or indications of an instrument with that of another, more trustworthy. However, the comparison leads certain difference between both responses. Regarding the discrepancies in such comparison, there exists an adjustment by which both indications are linked, in other words, there exists an adjustment that fits both discrepancies in order to make the instrument to “read correctly” (considering correct as the most trustworthy response). Then, it is obtained a numerical coefficient (the ratio of what you want or what you get from the most trustworthy instrument, divided by what you really get from the calibrated instrument) by which readings should be multiplied in order to give the correct reading. This factor is known as calibration factor and is normally associated with its own specific uncertainty according to the calibration procedure.

The measurement standard or standard may be defined as a reference by which a quantity, a quantity value and its associated uncertainties are clearly determined. (Centro Español de Metrología, 2012) The reference or standard appears on the comparison of the response of different instruments, so called calibrations. Such calibrations are set up by a consecutive number of comparisons in which the uncertainties gets worse after each comparison. So, the more calibration for any quantity is performed, the more uncertainty is introduced at each calibration, then more uncertainty for each standard quantity. This fact is setting up the level on where the standard lies, depending on the amount of uncertainty. In a whole, this is so called the traceability¹ of a measurement standard. (Cornejo, 2018)

The traceability of a measurement standard is moderated by a set of consecutive international and national organism who administer the maintenance of standards around the globe. However, due to an expansion and growing of metrology field, there are different special agencies who gather experts for each specific branch. In case of ionizing radiation, there is the Consultative Committee

¹ It is usually named metrological traceability and the correct definition is: a property of measurement result whereby the result can be related to a reference through a documented unbroken chain of calibration, each contributing to the measurement uncertainty. This chain establishes the metrological hierarchy of measurement. (Centro Español de Metrología, 2012)

for Ionizing Radiation (CCIR) at an international level. Such organism takes over the metrology that is linked with Ionizing Radiation and controls the international standards. Moreover, there exist the National Metrology Institutes (NMI) who transfer the equivalence of such international standards to national. This entity sets regulations of national standards for each nation and lays down the 1st level in traceability as a whole.

In Spain, the “Centro Español de Metrología”(CEM) and its associated laboratories establish and save the national measurement standards which were declared legal by “Ley 3/1985” at 18th March. Every certificate performed by CEM or associated laboratories has been accepted by international entities before a long period of revisions. Such revisions underwent a set of requirements from a system of quality management which is based on EN ISO/IEC 17025 standard. However, the spreading of every unit of measurement around Spain is by means of a tender of calibration laboratories which are attested and supervised by “Entidad Nacional de Acreditación” ENAC who follows statements from ISO 17025 and has the duty to accredit every calibration laboratory.

2.1. Calibration laboratories

2.1.1. Reference ISO 4037 standard

In the field of metrology of ionizing radiation, the International Standard Organization (ISO) published in 1979 the first ISO-4037 standard, defining X and gamma reference radiation for calibrating dosimeters and doserate meter and for determining their response as a function of energy. The standard was lately reviewed and splitted into 3 section. The current versions of the standard are:

1. ISO 4037-1. It specifies the characteristics and methods of X and gamma reference radiation for calibrating protection level dosimeters and rate dosimeters at air kerma rates from 10 $\mu\text{Gy/h}$ to 10 Gy/h and for determining their response as a function of photon energy. Specifically, it includes the energy range 600 keV to 1.3 MeV for gamma radiation emitted by radionuclides. (ISO, 1996)
2. ISO 4037-2. It specifies the procedures for dosimetry of X and gamma reference radiation for the calibration of radiation protection instruments over the energy range from 8 keV to 1.3 MeV. (ISO, 1997)
3. ISO 4037-3. It specifies the procedures for calibration of personal dosimeters and doserates meters used for individual and for area monitoring in photon reference radiation fields with mean energies between 8 keV and 9 MeV. Also this part deals with determination of the

response as a function of photon energy and angle of radiation incidence. Finally, this part presents the conversion coefficient factors to determine the operational quantities used in radiological protection. (ISO, 1999)

4. ISO 4037-4. It gives guidelines on additional aspects of the characterization of low energy photons radiations. This part also describes procedures for calibration and determination of the response of area and personal dose rate meters as a function of photon energy and angle of incidence. (ISO, 2008)

ISO 4037 series have been reviewed in 2019 (ISO, 2019). Some changes, in particular in the calibration set-up for gamma calibration, are introduced but they are not relevant for the objective of the project.

This project deals with radiation qualities emitted by gamma nuclides, in particular with the qualities identified in ISO 4037-1 as S-Cs and S-Co, which correspond to ^{137}Cs and ^{60}Co , respectively.

Radionuclide	Radiation energy keV	Half-life days
^{60}Co	1 173,3 1 332,5	1 925,5
^{137}Cs	661,6	11 050 ^[13]

Table 1. Radionuclide properties. (ISO, 1996, p. 16)

To fulfil the ISO 4037 requirements, the sources used for calibration, must be as small as possible so as to approximate them as a punctual sources and mitigate impurities effects to air Kerma (3.2.3.1 Kerma) below 1%. Also ISO establishes that sources must be encapsulated. Those capsules shall be sufficiently thick to absorb the beta radiation from sources (^{137}Cs and ^{60}Co). (ISO, 1996)

3. Quantities and units of radiation protection

Radiation protection monitors measure several quantities depending on their design or purpose of use. This section is intended to define the most relevant quantities used for calibration of radiation protection instruments and their relationship with the radiological quantities defined in the Directive 2013/59 to establish the dose limits for workers and workplaces. Such Directive is based on the ICRP recommendations. (ICRP, 2007)

It is important to distinguish a quantity from a unit. In everyday language the word quantity means amount, but in the field of measurement ‘quantity’ refers to a physical phenomenon in terms that are suitable for numerical expression. A physical quantity is a phenomenon capable of expression as the product of a number and a unit. A unit is a selected reference sample of a quantity. (Centro Español de Metrologia, 2012)

3.1. Protection quantities

Protection quantities are used to specify exposure limits to ensure that the occurrence of stochastic health effects is kept below unacceptable levels and that tissue reaction are avoided. The two protection quantities defined in the Directive 2013/59 are the equivalent dose in a specified organ or tissue T , H_T , and the effective dose, E .

3.1.1. Equivalent dose and radiation weighting factors

The definition of this protection quantity is based on the average absorbed dose, $D_{T,R}$ in the volume of a specified organ or tissue T , due to radiation of type R . (ICRP, 2007)

The radiation R is given by the type and energy of radiation either incident on the body or emitted by radionuclides residing within it. The protection quantity equivalent dose in an organ or tissue, H_T , is then defined by:

$$H_T = \sum_R w_R \cdot D_{T,R} \quad (1)$$

The absorbed dose, $D_{T,R}$, is the quotient of $d\bar{\epsilon}$ by dm , where $d\bar{\epsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm in an organ or tissue T . w_R is the radiation weighting factor

for radiation type R. This factor is characterized by the linear energy transfer (LET)¹, so high-LET radiation leads to large radiation weighting factor. The following table shows factors depending on radiation type:

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons ^a and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy

All values relate to the radiation incident on the body or, for internal radiation sources, emitted from the incorporated radionuclide(s).

Table 2. Recommended radiation weighting factors. (ICRP, 2007, p. 64)

The unit of equivalent dose, H_T , is $J\ kg^{-1}$ with the special name sievert (Sv).

3.1.2. Effective dose and tissue weighting factors

The effective dose, E , is defined by a weighted sum of tissue equivalent doses as (ISO, 2007):

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R} \quad (2)$$

where w_T is the tissue weighting factor for tissue T and $\sum w_T = 1$. The sum is performed over all organs and tissues of the human body considered to be sensitive to the induction of stochastic effects. These w_T values are chosen to represent the contributions of individual organs and tissues to overall radiation detriment from stochastic effects. The unit of effective dose is $J\ kg^{-1}$ with the special name sievert. (ICRP, 2007)

¹ LET is the average linear rate of energy loss of charged particle radiation in a medium, i.e., the radiation energy lost per unit length of path through a material. That is, the quotient of dE by dl where E is the mean energy lost by a charged particle owing to collisions with electrons in traversing a distance dl in matter. (ICRP, 2007)

On the basis of epidemiological studies on cancer induction in exposed populations, and risk assessments for heritable effects, a set of w_T values was chosen for these recommendations, Table 3, based on the respective values of relative radiation detriment. They represent mean values for humans averaged over both sexes and all ages and thus do not relate to the characteristics of particular individuals.

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
Total		1.00

* Remainder tissues: Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate (♂), Small intestine, Spleen, Thymus, Uterus/cervix (♀).

Table 3. Recommended tissue weighting factor. (ICRP, 2007, p. 65)

3.2. Operational dose quantities

The human body-related protection quantities, equivalent dose in an organ/tissue and effective dose, are not measurable. To overcome these practical difficulties for external photon irradiation, ICRU introduced and defined a set of operational dose quantities, which can be measured and which are intended to provide a reasonable estimate for the protection quantities.

These are the recommended quantities to be used by radiation protection instruments and are thus the quantities of major interest for the LCD calibration laboratory. On the other hand, such operational dose quantities are based on reference quantities which can be measured directly by laboratory's instruments. Those reference quantities are kerma or exposure and are introduced later on. (ICRU, 1985).

Different operational dose quantities are required for different tasks in radiological protection. These include area monitoring for controlling the radiation in workplaces and for defining controlled or restricted areas, and individual monitoring for the control and limitation of individual exposures. As a consequence, in a given situation, the radiation field 'seen' by an area monitor free in air differs from that 'seen' by a personal dosimeter worn on the body where the radiation field is strongly influenced by the backscatter and absorption of radiation in the body. The use of different operational dose quantities reflects these differences regarding its application. Table 4 shows the different operational dose quantities for every application of operational dose quantities for monitoring of external exposures.

Task	Operational dose quantities for	
	Area monitoring	Individual monitoring
Control of effective dose	Ambient dose equivalent, $H^*(10)$	Personal dose equivalent, $H_p(10)$
Control of dose to the skin, the hands and feet.	Directional dose equivalent, $H'(0.07, \Omega)$	Personal dose equivalent, $H_p(0.07)$
The lens of the eye	Directional dose equivalent, $H'(3, \Omega)$	Personal dose equivalent, $H_p(3)$

Table 4. Application for operational dose quantities for monitoring of external exposure. (ICRP, 2007, p. 297)

3.2.1. Operation quantities for area monitoring

The operational quantities are based on point doses determined at defined locations in defined phantoms. One such phantom is the ICRU-sphere. It is a sphere of 30 cm diameter with a density of 1 g/cm³ and a mass composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen. For practical calibration work, the ICRU-sphere can be replaced by a square block with the same composition and with the dimensions 30 cm x 30 cm x 15 cm. (ICRP, 1980)

The ambient dose equivalent, $H^*(10)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of 10 mm on the radius vector opposing the direction of the aligned field. The unit in SI for ambient dose is J kg⁻¹ or Sv. (ICRP, 1988)

In most practical situations of external radiation exposure, the ambient dose equivalent fulfils the aim of providing a conservative estimate or upper limit for the value of the limiting protection quantities. This is not always the case for workers in high energy radiation fields.

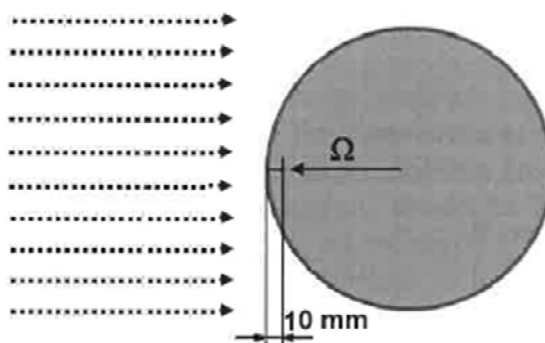


Figure 1. Diagram of ambient dose equivalent $H^*(10)$. (Cornejo, 2018, p. 1.46)

The directional dose equivalent, $H'(d, \Omega)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field¹ in the ICRU sphere at a depth, d , on a radius in a specified direction Ω . For low-penetrating radiation it is $d = 0.07$ mm, and $H'(d, \Omega)$ is then written $H'(0.07, \Omega)$. However, for unidirectional field, directional dose equivalent is usually written as $H'(0.07, \alpha)$, where α is angle between Ω direction and the opposite unidirectional field vector (See Figure 2). In the case of monitoring the dose to the lens of the eye, $H'(3, \Omega)$ with $d = 3$ mm was recommended by ICRU. (ICRU, 2011)

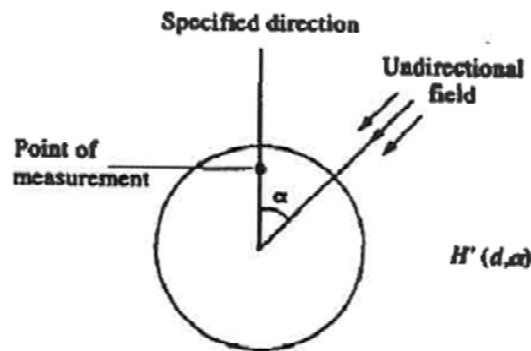


Figure 2. Diagram of directional dose equivalent $H'(d, \alpha)$. (Cornejo, 2018, p. 1.47)

Calibration laboratories normally use a punctual radioactive source to define the gamma beam by a reference quantity² like air kerma or exposure (3.2.3.1 *Kerma* and 3.2.3.2 *Exposure*) Then, conversion coefficients are intended to be used for transforming reference quantities to operational dose quantities, according what is published in ISO 4037-3 standard for X and gamma fields.

For environmental monitoring the ISO 4037-3 standards recommends different conversion factor to introduce a link between the operational dose quantity in use with the reference quantity (air kerma in such case). Regarding area monitoring, the operational dose quantity is the ambient dose equivalent $H^*(10)$ and $H'(0.07, \alpha)$ the directional dose equivalent. The conversion coefficient

¹ An expanded radiation field is a radiation field in which the spectral and the angular fluence have the same value in all points of a sufficiently large volume equal to the value in the actual field at the point of interest. The expansion of the radiation field ensures that the whole ICRU sphere is thought to be exposed to a homogeneous radiation field with the same fluence, energy distribution and direction distribution as in the point of interest of the real radiation field. (ICRU, 1985)

² It is the most fundamental quantity by which all instrument of a calibration laboratory are based. That quantity must be physically measurable and be considered as an instrument, so gamma beam may be relied on the reference quantity.

$h_k^*(10; S)$ and $h_k^*(0.07; S; 0^\circ)$ for radiation qualities used in this project are shown in Table 5 and Table 6. (ISO, 2019)

Radiation quality	Irradiation distance [m]	$h_k^*(10; S)$ [Sv /Gy]
S-Cs	1.0 – 3.0	1.21
S-Co	1.0 – 3.0	1.16

Table 5. Recommended conversion coefficient $h_k^*(10; S)$. (ISO, 2019, p. 26)

Radiation quality	Irradiation distance [m]	$h_k^*(0.07; S; 0^\circ)$ [Sv /Gy]
S-Cs	1.0 – 2.5	1.20
S-Co	1.0 – 2.5	1.16

Table 6. Recommended conversion coefficient $h_k^*(0.07; S; \alpha)$. (ISO, 2019, p. 14)

3.2.2. Operation quantities for individual monitoring

Individual monitoring of external exposure is usually performed with personal dosimeters worn on the body, and the operational quantity defined for this application takes this situation into account. The operational quantity for individual monitoring is the personal dose equivalent, $H_p(d)$.

The personal dose equivalent, $H_p(d)$, is the dose equivalent in ICRU tissue at an appropriate depth, d , below a specified point on the human body. For the assessment of effective dose a depth $d = 10$ mm is recommended, and for assessing equivalent dose to the skin, and to the hands and feet, a depth $d = 0.07$ mm. In special cases of monitoring the dose to the lens of the eye, it has been proposed that a depth $d = 3$ mm would be appropriate. (ICRU, 1985)

$H_p(d)$ is used to assess the effective dose and should provide a conservative estimate under nearly all irradiation conditions. This, however, requires that the personal dosimeter be worn at a position on the body which is representative with respect to the exposure. For a dosimeter position in front of the trunk, the quantity $H_p(10)$ mostly furnishes a conservative estimate of E even in cases of lateral or isotropic radiation incidence on the body. In cases of exposure from the back only, however, a dosimeter worn at the front side and correctly measuring $H_p(10)$, will not appropriately assess E . Also in cases of partial body exposures the reading of a personal dosimeter may not provide a representative value for the assessment of effective dose.

In order to reproduce $H_p(d)$ in calibration laboratories, several phantoms are defined in ISO 4037-3 (ISO, 1999):

1. Trunk: 30 cm x 30 cm x 15 cm block with PMMA walls (front wall 2.5 mm thick and other walls 10 mm thick) filled with water and termed the ISO water slab phantom. When using radiations with a mean energy equal to or above that of the radionuclide ^{137}Cs , a solid PMMA slab of the same outer dimensions may be used. This phantom is used for personal dose equivalent $H_p(10)$ and also $H_p(0.07)$. This standard phantom is so called slab.
2. Extremities: An ISO pillar phantom water-filled hollow cylinder with PMMA walls and outer diameter of 73 mm and length of 300 mm. The cylinder walls have a thickness of 2.5 mm and the end faces have a thickness of 10 mm. This phantom is used for personal dose equivalent $H_p(0.07)$.
3. Fingers: Solid cylinder of PMMA, 19 mm of diameter and 300 mm long. This phantom is used for personal dose equivalent $H_p(0.07)$.
4. Eye lens: A new phantom has been proposed within ORAMED for the calculation of conversion coefficients from air kerma to $H_p(3)$. (Mariotti, 2009) For calibration purposes, a cylindrical phantom 200 mm of diameter and 200 mm long with a 5mm-thick PMMA wall filled with water has been proposed. This new phantom is included in the reviewed ISO 4037. (ISO, 2019)

For personal monitoring the ISO 4037-3 standards recommends different conversion coefficient to introduce a link between the operational dose quantity in use with the reference quantity (air kerma in such case). The operational dose quantity is the personal dose equivalent $H_p(10)$, $H_p(3)$ and $H_p(0.07)$. The conversion coefficient depends also on the phantom in use, so the following tables are sorted by so. In this case, it is recommended $h_{pk}(10; S; \alpha)$ for slab phantom (See Table 7), $h_{pk}(0.07; S; \alpha)$ for both slab and pillar phantom (See Table 8 and Table 9) and $h_{pk}(3; S; \alpha)$ for cylinder (See Table 10).

Radiation quality	Irradiation distance [m]	$h_{pk}^*(10; S; 0^\circ)$ slab [Sv /Gy]
S-Cs	1.0 – 4.0	1.21
S-Co	1.0 – 4.0	1.15

Table 7. Recommended conversion coefficient $h_{pk}(10; S; 0^\circ)$. (ISO, 2019, p. 51)

Radiation quality	Irradiation distance [m]	$h_{pk}^*(0.07; S; 0^\circ)$ slab [Sv /Gy]
S-Cs	1.0 – 4.0	1.21
S-Co	1.0 – 4.0	1.17

Table 8. Recommended conversion coefficient $h_{pk}(0.07; S; \alpha)$ for slab phantom. (ISO, 2019, p. 40)

Radiation quality	Irradiation distance [m]	$h_{pk}^*(0.07; S; 0^\circ)$ pill [Sv /Gy]
S-Cs	2.5	1.14
S-Co	2.5	1.13

Table 9. Recommended conversion coefficient $h_{pk}(0.07; S; \alpha)$ for pillar phantom. (ISO, 2019, p. 37)

Radiation quality	Irradiation distance [m]	$h_{pk}^*(3; S; 0^\circ)$ cyl [Sv /Gy]
S-Cs	1.0 – 4.0	1.18
S-Co	1.0 – 4.0	1.14

Table 10. Recommended conversion coefficient $h_{pk}(3; S; \alpha)$ for cylinder phantom. (ISO, 2019, p. 44)

3.2.3. Reference quantity

3.2.3.1. Kerma

Kerma is the reference quantity for standard chambers of LCD Secondary calibration laboratory. Kerma (K), is a quantity defined for ionizing uncharged particles as the quotient of dE_{tr} by dm , where dE_{tr} is the mean sum of the initial kinetic energies of all the charged particles liberated in a mass dm of a material by the uncharged particles incident on dm , thus:

$$K = \frac{dE_{tr}}{dm} \quad (3)$$

The special name for the unit of kerma is gray (Gy).

Although kerma is a quantity that concerns the initial transfer of energy to matter, it is sometimes used as an approximation to absorbed dose. The numerical value of kerma approaches to absorbed dose whether charged particle equilibrium exists. If there exist an equilibrium between each secondary particle, a negligible attenuation contribution and a slight binding energy, absorbed dose can be obtained by using kerma at a specific point:

$$D \approx K (1 - g) \quad (4)$$

Where g is the fraction of the kinetic energy of the electrons liberated by photons that is lost in radioactive processes in air. For photon energies below 1.25 MeV, $g < 0.003$, so (4) may be approximated as (Cornejo, 2018):

$$D = K \quad (5)$$

This approximation is possible due to the Charged Particles Equilibrium principle (CPE). (ICRU, 2011)

3.2.3.2. Exposure

The exposure, X , is the quotient of dQ by dm , where dQ is the absolute value of the mean total charge of the ions of one sign produced when all the electrons and positrons liberated or created by photons incident on a mass dm of dry air are completely stopped in dry air, thus

$$X = \frac{dQ}{dm} \quad (6)$$

The old unit for exposure was röntgen (R) and its conversion factor to SI is:

$$1 R = 2.58 \times 10^4 C \cdot kg^{-1} \quad (7)$$

The ionization produced by electrons emitted in atomic/molecular relaxation processes is included in dQ . The ionization due to photons emitted by radiative processes (i.e., bremsstrahlung and fluorescence photons) is not included in dQ . Except for this difference, significant at high energies, the exposure, as defined above, is the ionization analogue of the dry-air kerma.

For photon energies of the order of 1 MeV or below, for which the value of g is small, exposure can be further approximated by $X = (e/W)K_{air}$, where K_{air} is the dry-air kerma for primary photons, e is the charge of the electron and W is the mean energy to create a pair of ions. In other terms, exposure is straightly related with air kerma, so it is normally referred as the analogue to kerma referenced magnitude.

Since the quantity exposure is still used by some old radiation protection instruments, so also the LCD provides calibration in exposure despite of the fact that it is not recommended by directives or ICRU standards.

4. Secondary Standard Calibration Laboratory (Laboratori de Calibratge i Dosimetria LCD) at the Institut de Tècniques Energètiques

This section describes the secondary standard calibration laboratory LCD at INTE, how the calibration is carried out, from the reception of radiation protection instruments up to the emission of their certification with the respective delivery and a brief description of the main equipment in use for such calibrations. All those procedures have been elaborated for a complete fulfillment of quality ISO standard 17025.

In addition, the section provides a deeper insight on standard chambers of LCD, its traceability to the German National laboratory PTB and the procedure to obtain the gamma beam characterization.

4.1. Introduction

The aim of LCD is to provide a calibration service of ionizing radiation. The most common services include the calibration of environmental and radiation protection instruments and personal dosimeters with photon and beta radiation and surface contamination monitors with extended beta and beta gamma sources. It also performs irradiation of personal dosimeters, both passive and active.

To grant an appropriate service, that fulfills ISO 17025 quality standard, a set of internal procedures have been developed. S2A002, an internal procedure, establishes the technical administrative workflow for the LCD:

1. Offer: It is a document where the economic conditions, calibration and general conditions are described. Such document shall be properly signed by the client so as to start the calibration service.
2. Instruments reception: In general terms, the radiation protection instruments are directly sent to LCD. Reception is registered in a data base by an authorized technician.
3. Functioning check: First of all a technician has to check whether the instrument runs properly. If it stands the test, the procedure goes ahead. Otherwise, the technical director of LCD has to report such issue to the clients.
4. Main calibration: Instruments are calibrated following technical internal procedures derived from international standards and recommendations. Once the calibration is successfully performed, the certificate with the results is issued. Every instrument is assigned by a specific and invariant number identification which is reported on the

certificate. The certificate includes all the relevant information about the calibration process, environmental conditions and the final results: Calibration factor and its uncertainty. The certificate is prepared and signed by authorized staff and then reviewed and validated by the technical director. A calibration label is attached to instruments before packaged. Finally the instrument is ready to be sent back.

5. The return of instrument: Clients are notified through an email that their equipment is ready to be collected. The client is responsible to organize the collection of the instrument.
6. Invoice: The technical director of LCD validate invoicing order, prepared by the LCD staff. The invoice is then prepared by the centralized UPC administration department which continues with the invoicing services.
7. Certificate: Once the invoice is paid, the certificates are sent to clients.

All those procedures are monitored by an excel programme. Such programme is compiled in a single excel file called “full_seguiment.xlsm” that registers all radiation instruments in LCD.

4.2. The photon irradiation room

LCD is located at Diagonal 647, Barcelona in ETSEIB building. In the interest of this project, this part is focused in the description of the photon irradiation laboratory in which gamma calibrations are performed.

4.2.1. Photon calibration laboratory

It is a rectangular room of 17.80 x 5.9 m and 4.5 m high, separated into two compartments: the control room and the irradiation room.

In the control room there is all the control instrumentation and the operator workplace. The control room communicates with the irradiation room through a shielded door that ensures that operator can work in safe conditions from a radiological protection point of view.

The gamma irradiation room is where the photon irradiator is located. The photon irradiator contains 8 point gamma sources in a lead shielding which produce the calibration gamma beams. The calibration room is shielded to fulfil the radiation protection regulation.



Photo 1. Control room. (Taken by the author)



Photo 2. Gamma irradiation room. (Taken by the author)

4.2.2. Gamma irradiator

A gamma irradiator, ref. NI-641, manufactured by Nuclear Iberica, stores 8 radioactive point sources. It consists of a cylindrical shielding of lead with a front collimator and an inner barrel in which sources are located. (See Appendix 1. Layout of NI-641)

Through a remote regulator in the control room, the operator selects the needed gamma source and situates it in the irradiation channel.

The next table shows some features about NI-641:

Diameter	560 mm
Length	950 mm
High of beam axis	1300 mm
Weight	1200 kg
Shielding	Lead
Designed radioactivity	1.85 TBq ^{137}Cs and 7.4 GBq ^{60}Co
Max. exposure outside shielding	9.33 $\mu\text{Sv/h}$
N° sources	8

Table 11. NI-641 features. (INTE, 1982)

4.2.2.1. Collimator

In order to collimate the radiation beam, the irradiator is designed with a collimator 223 mm long and a set of lead rings which produce a beam of 20 cm diameter at 1.0 m. The collimator, as well as limiting the beam dimensions, it reduces the contribution of Compton scattering produced due to the interaction between the gamma photon and the walls of the gamma irradiator. The 4037 standard provides recommendations about the design of the collimator. (See Appendix 2. Scheme of NI-641)

4.2.2.2. Shutter

It is a 12-cm lead cylinder, which is displaced along a vertical axis, in order to open the irradiation channel and let the gamma irradiation go out. When the shutter is closed, the maximum exposure rate in the outer face of the irradiator is below 10 $\mu\text{Sv/h}$.

4.2.3. Radioactive sources

The radioactive sources in the barrel are:

Source	Isotope	Nominal activity Ci	Emission date	Serial ID	Encapsulate
1	^{60}Co	0.5	28/02/1986	0109HD	X-540
2	^{137}Cs	30	01/06/1981	47EZ	X-60/1
3	^{137}Cs	2	17/12/1980	0086GN	X-19
4	^{137}Cs	0.5	16/12/1980	3799GN	X-19

5	^{137}Cs	0.2	17/12/1980	3799GN	X-8
6	^{137}Cs	0.02	28/11/1980	3500GM	X-8
7	^{137}Cs	0.002	28/11/1980	3817GM	X-8
8	^{241}Am	0.2	17/10/1980	4662LA	X-108

Table 12. Radioactive sources. (INTE, 1982)

The ^{241}Am source is not used anymore in the Laboratory for low photon energy calibrations, because the beams produced in the X-ray generator are preferred for the energy range 200 keV – 33 keV.

The encapsulations and the chemical form for each source fulfill the ISO standard 4037-1.

4.2.4. Calibration bench

The calibration bench consists of an aluminum carriage with a platform for the correct positioning of the detectors to be calibrated and a tape meter to select the distance source-detector.

The platform is moved from the control room by an electric motor with its corresponding gearwheels and transmission belt. The positioning system is made of aluminum so as to reduce photon dispersion of the incident beam with it.

The following table shows the main technical data of the calibration bench:

Technical feature	Value
Rail's operation length	6 m
Total length	8.40 m
Height	0.4 m
Motor	Clerely MR 36-35/511.
Power	36 W
Output speed	300 rpm
Control device	Direction displacement, speed control and stopping

Table 13. Bench's features. (INTE, 1982)

4.2.5. Safe and control system

4.2.5.1. Control operation

The control of the photon irradiation room is commanded by a set of different controllers and indicators. All those components are settled on gamma irradiator console (INTE prototype See Photo 3) for remotely controlling the positioning of radiation protection instruments and the photonic irradiator, fulfilling always safety conditions.

Indicators:

1. General power switch: Power all equipment (shutter motor, barrel motor and positioning motor).
2. Shutter indicator: Indicates the shutter position (Green – Close, Red – Open)

Controllers:

3. Power switch of positioning system: Turns on the electric feed to the positioning motor.
4. Displacement throttle of positioning system: Regulates speed of the electric motor.
5. Shutter control switch: Turns on the shutter opening.
6. Sources selector switch: Selects the position of the barrel.



Photo 3. Console. (Made by the author)

4.2.5.2. Safety operation

The goal of the safety system is to avoid exposure of workers during operation. Such goal is achieved by means of preventing access to the irradiation room by non-authorized workers or when the beam is on.

The access to the irradiation room is through a unique door. From the control room, the door is only opened by an authorized key. In the other side, the opening is always on hand, so that anyone in the radiation room should be able to leave it immediately.

Moreover, there exists an electric circuit for preventing exposure of workers if someone tries to go in during a calibration. This system produces an emergency stop in case of non-authorized entry. An electronic system triggers an emergency alarm while closing the shutter immediately. The emergency closing is fed by a set of accumulators which are got off from the electrical grid. This results in permanent and available safety systems.

In addition, in case of electricity shutdown or failure of any automatic control system, the shutter may be closed manually.

4.2.6. Reference detection system. Standard chambers

To characterize the photon radiation beams, the LCD measures the air kerma rate produced by the gamma sources in the NI-641 irradiator at different distances ranging from 1.0 to 6.5 m.

Measurements are performed using ionization chambers connected to an electrometer, with low noise that allow the measurement of low currents, previously calibrated in National or accredited laboratories. The LCD has several ionization chambers and several electrometers available for this purpose.

At present, the calibration of the gamma beams are performed with a 1 L spherical ionization chamber, the PTW type TM32002 model. It is connected to a PTW electrometer type Weblin T10021.

For the less active sources (Source number 5 and 6), a 10 L spherical chamber, Seibersdorf, type LS-10 is used. This chamber is connected to a Keithley 642 electrometer. TM32002 standard chamber is directly traced to the German national laboratory “Physikalisch-Technische Bundesanstalt” PTB and LS-10 is indirectly traced through the TM32002 chamber.

Both chambers are vented and designed for stationary radiation protection measurements, and for low level measurement free in air in secondary standard laboratories. The standard chamber TM32002 is designed to be used for the range between 18 $\mu\text{Gy/h}$ up to 225 Gy/h of air kerma with a chamber voltage of 400V (at nominal operation). (Physikalisch-Technische Werkstätten (PTW), Freiburg, 2009) Otherwise, LS-10 is used for the range between 2.2 $\mu\text{Gy/h}$ up to 27 Gy/h with voltage of - 400 V. (PTW, 2019)

4.2.6.1. PTB traceability

The national metrology laboratory in Germany, so called “Physikalisch-Technische Bundesanstalt” PTB, measures with the highest accuracy and reliability – metrology as the core competence.

PTB division 6 is concerned about the metrology of ionizing radiation. Its main tasks cover offering measuring techniques for the detection of ionizing radiation, dosimetry for radiotherapy, radiodiagnostics and radiation protection, radiation measurements in the environment, activity measurements and the determination of atomic and nuclear data. The units of activity, fluence rate, air kerma, absorbed dose and dose equivalent are reproduced and disseminated via calibrations. Within division 6, the department 6.3 concerns about radiation protection dosimetry. (Physikalisch-Technische Bundesanstalt, 2019)

The latest two calibrations of the 1 L PTW chamber at PTB were performed in 2013 and 2018 (PTB, 2018). This calibration ensures the traceability chain of LCD measurements to international calibration laboratories. After calibration, PTB issues a certificate with the calibration factor to refer the chamber reading, M , to the real value of air kerma, using the following equation:

$$K_a = N_k \cdot M \cdot k_q \cdot k_p \cdot k_e \quad (8)$$

Where N_k is the calibration factor in terms of the air kerma at reference conditions of 20°C and 1013,25 hPa, k_q is the correction factor for the radiation quality Q (radionuclide), k_p the correction factor for density at same boundary conditions and k_e the electrometer correction factor. A copy of the 2018 calibration certificate, with the calibration factors and the associated uncertainties is attached in Appendix 3. The factors to be applied for the gamma sources are shown in Table 14.

Factor	Value
N_k	$2.504 \times 10^4 \text{ Gy/C}$
k_q	^{60}Co : 0.982 at 2m.
	^{137}Cs : 0.996 at 1m
	^{137}Cs : 1.000 at 2m
$k_p = \varphi(P, T)$	Depends on calibration boundary conditions
k_e	1.00 for all ranges

Table 14. Calibration factors of TM32002. (Appendix 3)

LS-10 calibration is performed internally comparing the 1 L PTW chamber with the LS-10 using sources 4 and 5 at 3.5 m. The same equation is used to obtain air kerma. In this case the calibration factors N_k is $1.246 \times 10^{-6} \text{ Gy/V}$ reported in Appendix 4.

4.2.7. Auxiliary equipment for atmospheric conditions

Air temperature, humidity and pressure are relevant quantities which allow implementing atmospheric correction factors under certain limits. Regarding functional purpose, LCD has four different systems to regulate atmospheric conditions. The air temperature is controlled by a GENERAL INVERTER air conditioner in both irradiation and control room. The humidity is controlled by two different dehumidifier, MUNDOCLIMA and TRAUED2B in the control room and the irradiator room, respectively. Such systems are able to maintain atmospheric conditions between 15 up to 25 °C for temperature and 20 up to 70% for relative humidity in order to apply the correction factor for standard chambers (See Equation (10))

For the measurement of the atmospheric conditions, LCD owns the following instruments:

Instrument	Functional accredited range
Barometer Wallace Tiernam	750 – 1060 hPa
E+E ELECTRONIK EE 160 + NOVUS FIELDLOGGER	15.1 – 30 °C and 11.7 – 95% relative humidity
Thermometer YSI 400	9.8 – 30.8 °C

Table 15. Auxiliary equipment. (LCD Manuals)

For measuring time, the lab uses a manual stopwatch CASIO HS 10 W. It has a long operational and accredited range up to 21,600 seconds. For some measurements, an internal chronometer of the electrometers are used.

All instruments in use must be calibrated by authorized laboratories with their corresponding accreditation. The calibration factors and associated uncertainties must be known in the range of interest.

5. Determination of the photon beams equations

This section describes the procedure followed to obtain the gamma beam equation based on LCD calibration procedure S2C002¹ using air kerma as a reference quantity. This part is composed of an initial description of the practical assembly to calibrate the gamma beam and the subsequent calculations and results for obtaining the beam equation and its corresponding parameters.

5.1. Introduction

There are two possible options to calibrate radiation protection instruments. Firstly, calibration can be performed by the so called replacing method which consists in a direct comparison between the standard chamber and the instrument to be calibrated. This technique is time-consuming and is mainly used to calibrate reference instruments. The second method consists in characterizing the gamma beam with the standard chamber and obtaining a parametric equation whereby the radiation protection instrument may be calibrated. That option is the preferred one for field instruments and is the method that this section deals with.

The procedure S2C002 describes the experimental set up and the following calculations for carrying out the characterization of gamma beams. Such process determines an equation which associates position with air kerma rate. Then, the required calculations are performed by two programs, “Beam” and “Beamedit”, developed by INTE.

As example, this project includes the measurement and calculations corresponding to the gamma beam calibration of source n°2. The calibration of gamma beam for source n°2 was performed in 28th October 2018 following procedure S2C002. Such results are shown on the attached report “Informe de calibración interna” in appendix 5.

5.2. Measurements

The standard chamber used has to have a calibration factor for the energy of interest, a good sensitivity for the required dose rate range and a diameter smaller than the dimension of the beam at the point of the measurement. The TM32002 with the electrometer PTW UNIDOS Weblin has been selected to calibrate beam equation of the source n°2. The characteristics of these instruments are described in 4.2.6 *Reference detection system. Standard chambers* at page 29.

¹ Such procedure was written by INTE staff as internal procedure and it is based on ISO 4037 standards.

Before starting measurements, the chamber must be irradiated with approximately 20mGy at 1 m so as to warm up the ionization chamber.

Subsequently, the standard is irradiated with the selected sources to perform measurements at 12 different points: 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6 and 6.5 meters. Generally the measurements are performed with three independent readings at each point ($n_{j,h} = 3$). Once they are done, the process may be repeated H_j times (normally $H_j = 1$). If the repeatability of the standard chamber is not already known, the number of independent readings should change to 5 ($n_{j,h} = 5$) so as to determine the statistical uncertainty for such readings.

Approximately, at half-time of each measurement, the pressure and temperature of the irradiation room are recorded on the data collection sheet¹ in order to reduce readings to normal environmental conditions.

Once the 3 or 5 readings are performed, the standard chamber is moved to the next calibration point and the process is repeated again until the end (12 points for all range).

For subsequent corrections, initial and final leakage are measured at the beginning and the end of each work. The leakage readings are recorded with the pressure and temperature values too.

5.3. Calculation

The experimental data are stored in several files following the instructions in procedure S2C002 for further calculation. The required files to obtain the beam adjustment equation are:

1. FUE*****.dat: This file has to have 8 characters length at most. Such file contents general information about source: identification number, alphabetic reference, calibration date of beam, radionuclide in use, mass attenuation coefficient, parameters A and B of the linear regression line and the maximum and minimum available distance for each source. In the example case, file FUE17.dat is plotted in appendix 5.
2. DETECT**.dat: This file has to have also 8 characters length at most. It stores data about the detector in use: absolutes and relative uncertainties, uncertainties of scale readings and the calibration factor with the corresponding uncertainty for every source located at

¹ The data collection sheet for the calibration of gamma beam of sources nº2 is plotted in Data collection sheet of calibration on appendix 6.

FUE17.dat file. In the example case reported on appendix 5, the DETECT18.dat values of the TM32002 2018 calibration are included.

3. FNAA**.dat: The N is the identification number of the source in use, AA is the year date of measurements and two more characters are available for any additional purpose. In the “Internal Calibration Report” F218.dat is used. Such file identifies detector file, source file, the source number and the date of the measurements. It also includes all data reported in the data collection sheet (Appendix 6). In this case, readings are in terms of charge (Coulombs) which are subsequently converted into air kerma with Equation (9) to obtain the beam equation further on.

Once all necessary data is properly introduced, it is time to run the “Beam” programme. The air kerma rate at each experimental distance is calculated by the following equation:

$$\bar{K}_j = N_k \cdot k_q \cdot k_e \cdot \frac{1}{n_j} \cdot \sum_{i=1}^{n_j} \left(\frac{L_{j,i}}{t_{j,i}} - \dot{F}_j \right) \varphi(P_{j,i}, T_{j,i}) \quad (9)$$

k_q and k_e correspond to calibration factors reported by PTB in the certificate (See Table 14). $L_{j,i}$ are individual readings of charge (Coulombs) at d_j distance, \dot{F}_j is the average leakage rate, $t_{j,i}$ is the irradiation time and $\varphi(P_{j,i}, T_{j,i})$ is the pressure and temperature correction factor. The last factor is obtained by Equation (10) which refers readings to standard atmospheric conditions ($P_0 = 1013.25 \text{ hPa}$ and $T_0 = 293.15 \text{ K}$)

$$\varphi(P, T) = \frac{P_0}{P} \cdot \frac{T}{T_0} \quad (10)$$

Once the air kerma is obtained, the programme derives the beam equation through a least square approximation fits according to the following equation:

$$\frac{1}{\sqrt{\dot{K}_j \cdot e^{\left(\frac{\mu}{\rho}\right) \chi_j}}} = A \cdot d_j + B \quad (11)$$

Where \dot{K}_j is air kerma rate [Gy/s] at distance d_j [m], χ_j massic distance [g/m²] ($\chi = \rho \cdot d_j$ where ρ is density and d_j distance), μ/ρ mass attenuation coefficient ¹[m²/g] and A and B the equation parameters obtained from the least square approximation.

Finally, after consecutive iterations, A and B are obtained. “Beams” programme returns such results at REGNAA.dat file plotted in appendix 5, where N character is assigned to source number (2 in such example) and AA to year (18 in the example). REG218.dat reports two different fitted equation:

1. It adjusts all data in a single equation.
2. It adjust the data splitting the equation in two parts. It is normally divided at distance $< 3m$ and $\geq 3m$.

Thus, the best equation is the one that reduces as low as possible the average relative error with the experimental data.

For each fitted equation, the following variables are shown:

1. Mu: The mass attenuation coefficient calculated by Beam programme (μ/ρ). REG18.dat plots Mu coefficients for each equation.
2. Dist: Distance from source point.
3. Kexp: The averaged measured air kerma rate (Gy/s) at distance Dist.
4. Inc.exp (%): Relative uncertainty (k=1) for Kexp.
5. Cap.Op. (%): Ideal measurement capacity of LCD (k=1). It indicates the minimum relative uncertainty for calibration process.
6. Kfit: The air kerma rate calculated by the fitted equation.
7. Inc. fit (%): Relative uncertainty (k=1) for fitted Kfit.
8. Exp-fit(%): Relative difference between the fitted equation and experimental values.

¹ The mass attenuation coefficient is defined from the database run by National Institute of Standard and Technology, specifically from XCOM database for dry-air. In case of source n° 2, ¹³⁷Cs with a photon decay of 661.657 keV at 85.10% yield has a mass attenuation coefficient for dry-air of 7.75 m²/kg. (M.J.Berger, et al., Retrieved 2 Nov 2007.)

9. a, b and r: Parameters and correlation coefficient of the equation.

In addition, “Beams” verifies that the scattered radiation is not above 5% from the primary radiation, as required by ISO 4037-1.

5.4. Results

Measurements and calculations are performed for the six available photon sources at LCD (4.2.3 *Radioactive sources*). The operator responsible for the calibration has to decide if the fitting is better using one or two lines. However, the equation normally fits better with experimental data if the equation is made up by two independent straight lines. In such experience, the proposed solution in appendix 5 for source n°2 is the equation in two parts.

Table 16 summarizes the fitting data obtained, for source number 2, in the last complete calibration in 2017 and the data from the calibration 2018 performed in the framework of this project (Appendix 5). All those data are used in the next part of this project.

Date	A1 [s ^{1/2} /m/Gy ^{1/2}]	B1 [s ^{1/2} /Gy ^{1/2}]	MU1 [m ² /g]	r1	A2 [s ^{1/2} /m/Gy ^{1/2}]	B2 [s ^{1/2} /Gy ^{1/2}]	MU2 [m ² /g]	r2
5/10/17	3.101e2	1.102	7.749e-3	0.999999	3.085e2	8.582	7.749e-3	0.999998
29/11/18	3.133e2	1.170	7.749e-3	0.999996	3.166e2	8.708	7.749e-3	0.999997

Table 16. Fitting data of the first and second equation (Appendix 5)

Table 17 shows the comparison of the experimental measurements obtained in this project for source n°2 and the fitted data using the Equation (11) with Table 16.

Distance [m]	V_{exp}^{2018} [Gy/s]	V_{fit}^{2018} [Gy/s]	$V_{fit}^{2017 \text{ with decay}}$ [Gy/s]	$\frac{V_{fit}^{2018}}{V_{exp}^{2018}}$	$\frac{V_{fit}^{2017 \text{ with decay}}}{V_{exp}^{2018}}$
1	9.99E-06	1.00E-05	9.96E-06	1.003	0.997
1.5	4.44E-06	4.44E-06	4.42E-06	1.000	0.995
2	2.50E-06	2.49E-06	2.48E-06	0.998	0.992
2.5	1.59E-06	1.59E-06	1.58E-06	0.998	0.992
3	1.10E-06	1.10E-06	1.09E-06	1.002	0.996
3.5	8.02E-07	8.01E-07	7.96E-07	0.999	0.992
4	6.12E-07	6.12E-07	6.08E-07	1.000	0.993

4.5	4.81E-07	4.82E-07	4.79E-07	1.002	0.996
5	3.89E-07	3.89E-07	3.86E-07	1.000	0.993
5.5	3.20E-07	3.20E-07	3.18E-07	1.000	0.993
6	2.68E-07	2.68E-07	2.66E-07	1.000	0.993
6.5	2.28E-07	2.28E-07	2.26E-07	1.000	0.993

Table 17. Comparison of experimental and calculated air kerma rate from 2017 and 2018 calibration. (Appendix 5)

6. Feixos99

The aim of this section is to present the programme that is going to be updated in this project. Feixos99 is a programme that, based on the photon beam equation described in chapter 5. *Determination of the photon beams equations*, calculates where to situate an instrument for its calibration. It includes a brief description of the system as black box representation and its input and output variables, how such programme is implemented, the calculation method in use and possible updating for the next version “Feixos19”.

6.1. Introduction

Feixos99 is the programme used at present at LCD for determining the position of instruments for their calibration. The beam equations obtained with “Beams” are used for determining such position. Since the equation is a non-linear function, Feixos99 calculates the distance variable through a root-finding algorithm, so called iteration, for a nonlinear equation regarding distance quadratic form.

6.2. Black box description

In engineering a black box is a device or system which can be viewed in terms of its inputs and outputs without any knowledge of its internal working. Its implementation is “opaque” (black) that refers to unknown internal processing (Bunge, 1963). In this project, Feixos99 is built out as a black box in order not to show the unknown inner processing. Feixos99 is represented by a black box and may be set up by their inputs and outputs variables.

Feixos99 requires the following input variables:

1. Date: Date when the calibration is performed it is used to take into account for radioactive decay.
2. Pressure and temperature: It is needed to apply the air density attenuation corrections.
3. Source n°: The user indicates the source in use for the calibration.
4. Radiation quantity: The user selects the radiation quantity of the instrument to be calibrated. Feixos99 may deal with absorbed dose in tissue, exposure, air kerma, personal dose equivalent and ambient dose equivalent.
5. Target dose rate: It is the referenced radiation quantity value (dose rate).
6. Accumulative or rate: The user indicates if the calibration is in rate mode or integration. If the integration mode is selected, then the reference integrated dose value is required for obtaining irradiation time.

7. Target dose value: In case of accumulative mode, Feixos99 requires integration dose.
8. Open or close detector: The user selects if the detector requires correction of ambient conditions.
9. Table center shift: The user specifies, when needed, the distance between the detector reference position and the position table center.
10. Tissue thickness: If absorbed dose in tissue is selected as radiation quantity, the programme requires the corresponding tissue thickness.

The outputs are:

1. Distance: It is the calculated distance source-measurement point. It is the main output value.
2. Bench distance: It is the distance where to put the instrument, taking into account the table shift.
3. Calculated dose: It is the calculated dose rate at such distance.
4. Irradiation time: In case of accumulative mode, it plots total time to achieve the accumulative value.
5. Correct reading: It plots the corrected reading for open detectors.

The following diagram sum up Feixos99 as a black blox representation:

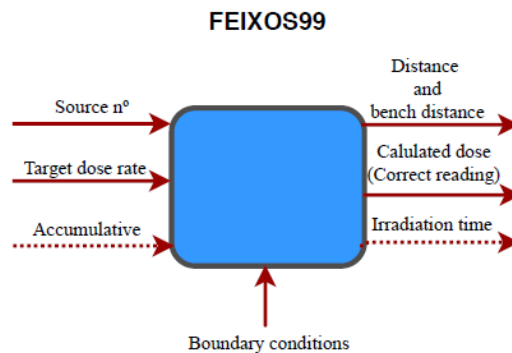


Figure 3. *Feixos99 as a black box representation. (Prepared by the author)*

Although the previous block may simplify the content of each software, it is interesting to expose the internal working for Feixos99. For fulfilling this statement, the following section goes deeper into the code which was written in DOS-basic. All code is split in several sections for processing different functions and overcome the completed task as a whole, resulting in the output variables.

6.3. Feixos99 code

The programme was written in DOS-basic code and saved into the corresponding FEIXOS99.bas file. The file stores 331 lines of coding which are sorted by an initial identification number which is going to be used for referring lines. Every line corresponds to a single command that can perform either an internal or input operation. Every command operation is run line by line with a command prompt window by which the technical staff is controlling the programme. Furthermore, the implemented code is straightly connected with a printer that is totally controlled by a command LPRINT.

Feixos99 code is sorted by 8 different sections:

1. Input: Here the command prompt windows asks the user for the input data. All specifications are introduced into it for a further on processing. (line 10 to 130)
2. REM subroutine: It fixes the conversion factor which depends on the target radiation quantity value and the selected sources n° from the input section. (line 500 to 610).
3. Defining air kerma. Once the parameters are loaded, it calculates the target air kerma for which the calculation algorithm will be looking.
4. Parameters loading 1. It loads the parameters A, B, MU, LD (decay constant) and the reference date for the corresponding beam equation in use. If the equation is split into two parts, it loads only the parameters of the first one. (line 1000 to 7110).
5. Air kerma range: It calculates the range for the selection beam equation and compares it with the target value which was introduced in the input section.
6. Calculation algorithm: If the value is in the first range, the distance is then calculated through a root-finding algorithm with a relative tolerance of 0.0001. (line 650 to 770)
7. Parameters loading 2. Otherwise, if the wanted air kerma is out of range, the programme loads the parameters from the second equation. Then it goes back to section number 5 for another calculation. (lines 1000 to 7110)
8. Plotting results: Once the calculation is finished, the air kerma is converted into the radiation quantity and printed in a sheet of paper. (lines 9000 to 10020)

All code is written down on Appendix 7.

6.3.1. Input section

The data is implemented through consecutive prompt commands which are asking the user for the inputs variables. It starts asking for day, month and year. Then the boundary atmospheric conditions are requested such as pressure and temperature. Feixos99 needs to know the source in

use, so it also asks for it. Once the source is selected, the programme orders to know which rate dose and radiation quantity are selected.

There are five different radiation quantities which are: Exposure in R/h, absorbed dose in tissue in rad/h¹, air kerma in mGy/h, personal dose equivalent in mSv/h and ambient dose equivalent in mSv/h. All those data must be entered using “dot” as a decimal separation.

Finally, it also asks for type of detector and the table center shift in meters.

6.3.2. REM subroutine

This subroutine is intended to apply the conversion factors presented in section 3.2 for obtaining the equivalent air kerma rate from the radiation quantity input data. Due to the fact that the input value is in mili, all factors are firstly divided over 0.001 (lines 510 to 560). Then, between line 601 to 610, factors are applied by a simple division. Moreover, if the absorbed dose in tissue is selected, the attenuation is calculated as $e^{-0.0886 \cdot GM}$, where GM is the depth of tissue. Also, at line 600, a factor of 3600 is introduced so as to convert time rate from hours to seconds, which is the unit used in Equation (12).

6.3.3. Parameters loading 1

Once the conversion factor is applied, the target equivalent air kerma is obtained. Then, the programme loads the 1st part of the beam equation parameters of the source in use.

6.3.4. Air kerma range

The programme calculates the limits of the air kerma range for the first part of the equation. It introduces firstly the atmospheric correction at 1013.25 hPa and 273.15 K for attenuation in the air due to changes in air density. Then calculates the decay factor and finally obtains the air kerma rate as:

$$\dot{K} = \frac{e^{(-MU \cdot 1.293 \cdot \varphi(P=1013.25 \text{ hPa}, T=273.15 \text{ K}) \cdot d)}}{(A \cdot d + B)^2} \cdot e^{(-\lambda \cdot \text{days})} \quad (12)$$

Where λ is the decay constant (d⁻¹) and days is the number of days (d) between the beams calibration date and the input date.

¹ rad/h is a old radiation unit. 1 rad/h = 10 mGy/h

Moreover, it checks whether the target value is within the limit of such range. If the air kerma rate is above the maximum limit, it reports a screen print “Exposició massa gran”. Similarly, if the target rate is below the minimum limit, the programme needs to load the second part of the equation.

6.3.5. Parameters loading 2

The programme goes to line 750 and calculates the minimum limit of air kerma with the parameters of the second part of the equation. Here, the programme checks the air kerma range again and, if it is out of range, it returns a screen print “Exposició massa petita” and comes back to line 30 asking for a new source.

6.3.6. Calculation algorithm

The calculation algorithm is a constant iteration that estimates air kerma value for a nonlinear equation. For obtaining the distance through air kerma value, an approximation for solving nonlinear methods is necessary. In this case, Feixos99 is using a constant step iteration, starting from the largest distance (minimum air kerma rate) to the smallest distance (maximum air kerma rate) for solving (11 (12).

The iteration starts from the largest distance and calculates the air kerma at that point. Then it goes further to low distance with a single step and calculates the air kerma at the new point. Here, it implements a conditional to observe whether the target distance is closer either to the minimum point or the maximum one. Then, it selects the correct side and approaches to the target distance with its corresponding target air kerma rate. Every distance and air kerma rate for each iteration are represented as D_p^i and X_p^i respectively.

Those procedures are constantly iterated until the error between X_{target}^i and X_p^i is below 0.0001 (See Equation (13)), where the X_{target}^i is the input target air kerma and X_p^i is the calculated in the iteration i .

$$\left| 1 - \frac{X_p^i}{X_{target}^i} \right| < 0.0001 \quad (13)$$

The step iteration is leaded by a factor step iteration according to the following Equation:

$$D_p^{i+1} = D_p^i + (-1)^k \cdot 10^{(1-k)} \quad (14)$$

where $k=1,2,3,4$ and 5 and D_p^i is the distance at iteration i . In line with the Equation (14), the new distance D_p^{i+1} may only differ a limited step from D_p^i . Depending on k value, the step $\Delta p = (-1)^k \cdot 10^{(1-k)}$ may vary as:

k value	$\Delta p = (-1)^k \cdot 10^{(1-k)}$
1	-1
2	+0.1
3	-0.01
4	+0.001
5	-0.0001

Table 18. Constant step iteration. (Appendix 7)

6.3.7. Result

In Feixos99, the results are plotted through an internal command LPRINT. However, before printing the results, the code transforms the equivalent air kerma into the radiology quantity which was defined at the input section (lines 9000 up to 10015). The appropriate conversion factors are used for restoring the previous radiology quantity and, for open instruments, the atmospheric correction is also calculated. Then all results are sent to the printer to continue the calibration process.

6.4. Taxa99

In some cases the calibration is performed at a given distance and the operator wants to know what the reference radiation quantity at that position is. The programme uses Equation (12) and provides as output the required value. This option is run separately through the programme called Taxa99. In this case, the problem is straight forward and the user only has to introduce:

1. Date: It is the date when the calibration is performed. It is necessary for applying the radioactive decay.
2. Pressure and temperature: It is needed to apply the air density attenuation.
3. Source n°: The user indicates the source in use for calibration.
4. Distance: It is the distance source-measure point where the user wants to calculate the reference radiation quantity.
5. Quantity: Radiological quantity needed at the selected distance

The output is the calculated radiation quantity at the selected distance.

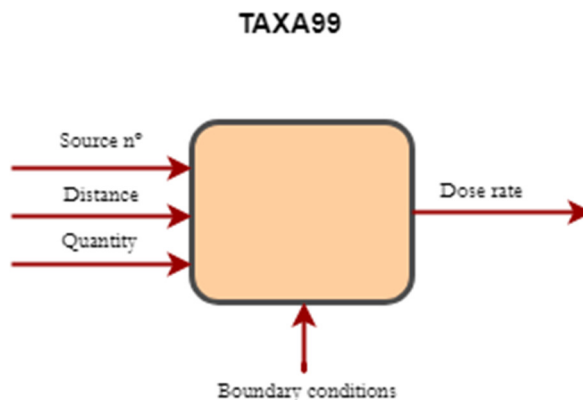


Figure 4. Taxa99 as a black box representation. (Prepared by the author)

6.5. Improvements in the new version of Feixos99

Several improvements were identified for the new version of Feixos99. The new programme is called Feixos19 and it is designed as an Excel® to integrate it to the rest of the management system in place at the LCD. To facilitate such integration, MS-Dos is changed to .xlsm file where macros¹ are available.

The new programme also should simplify the procedure to introduce the new beam equations and the conversion factors. To avoid selecting the source and improve user-friendliness, Feixos19 shall recommend the source to use for a given dose rate. Such recommendation will be based on a distance optimization where some positioning range will prevail over all. A new improved calculation algorithm based on the bisection approximation method for a nonlinear equation will also be implemented.

Feixos19 will implement a new inner block “Integrada” (See Figure 5) which will connect the equivalent Feixos99 and Taxa99 for merging both programmes in a single one.

After discussion among the LCD team, the calculations of the reading indication for an open detector which requires environment conditions corrections were eliminated, so the new software Feixos19 will not implement the correct reading variable.

¹ A macro is an automated input sequence that imitates keystrokes or mouse actions. A macro is typically used to replace a repetitive series of keyboard and mouse actions and are common in spreadsheet and word processing applications like MS Excel and MS Word. Reference: <https://docs.microsoft.com/en-us/office/vba/api/overview/excel>. Visit at: 05/02/2019

7. Feixos19

7.1. Introduction

The aim of this section is to introduce the new programme Feixos19. The improvements highlighted in paragraph 6.5 have been considered. The section starts with a Black box representation of the new programme. Joining the whole features in a single box with inputs and outputs, the updated programme is simplified. In addition, this section also deals with presentation of the code of the new programme in order to deepen into the basic functions, splitting them up into subdivided structures to ensure a better understanding of the programme. Finally, the debugging and verification is presented in the next sections.

The new programme merge all functions of Feixos99 and Taxa99 in a single Box. The new programming language is used to integrate it to the rest of the management system in place at the LCD.

7.2. The new black box

The new programme merges all functions of Feixos99 and Taxa99, so the new black box will use inputs and outputs of both former programmes. However, the input source number will become an output in Feixos19.

The inputs of Feixos19 are:

1. Date: It introduces the date when the calibration is performed for obtaining the decay factor. The new programme loads the current date from operational system's clock as default.
2. Pressure and temperature: It is needed to apply the air density attenuation corrections. Feixos19 requests a manual input, but offering affordable future changes for automatically loading these variables from laboratory's instruments.
3. Radiation quantity: The user selects the radiology quantity of the instrument to be calibrated. Feixos19 may deal with absorbed dose in tissue, exposure, air kerma, personal dose equivalent and ambient dose equivalent. There is no changes from Feixos99.
4. Target dose rate: It is the reference radiation quantity value (dose rate).
5. Accumulative or rate: The user indicates if the calibration is in rate mode only or integration is also required. If the integration is selected, then the reference dose value is required.

6. Table center shift: The user specifies the distance between the detector reference position and the position table center.
7. Tissue thickness: If absorbed tissue dose is selected as radiation quantity, the programme requires the corresponding thickness.

The outputs are:

8. Calibration distance: It is the calculated distance source-reference point. It is the main output value.
9. Bench distance: It is the distance indicated in the meter of the bench (a bench distance of 0.0 m is equal to a source-table center distance of 1.10 m).
10. Calculated dose: It is the calculated dose rate at the calibration distance.
11. Source n°: Recommended photon source. Feixos19 implements that variable as an output. The programme proposes the recommended source from a list. Subsequently, the technician confirms it or selects another one from the list.
12. Irradiation time: In case of integration mode, it plots total time to achieve the accumulated value.

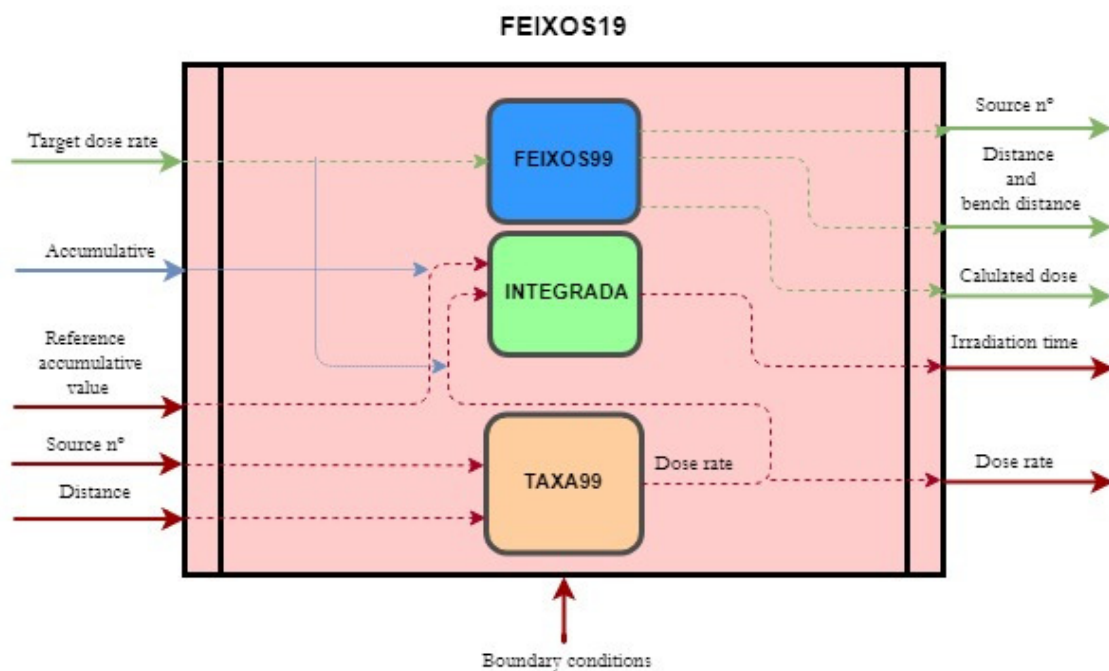


Figure 5. *Feixos19 as a black box representation. (Prepared by the author)*

The main goal of Feixos19 is obtaining the source n°, the distance and the calculated dose (Green arroww in **Figure 5**). Moreover, in some cases, the operator wants to know what the value of the reference radiation quantity at a certain point is. Feixos19 implements a secondary group of

variables: Reference accumulative value, Source n° and Distance (Red arrows in **Figure 5**). Finally, the subfunction “Integrada” by which the irradiation time might be obtained is implemented too. (Green block and the blue arrows in Figure 5)

7.3. Feixos19 code

The new software is compiled into an Excel® file. This file, so called “Feixos19.xlsm”, is separated in different sheets. There is the main sheet “Feixos” for interfacing every input variables and showing the main results, the sheet “Impressió” that implements printing settings and three more sheet “Dades”, “Llistes” and “Càlcul” which are intended to process and store data.

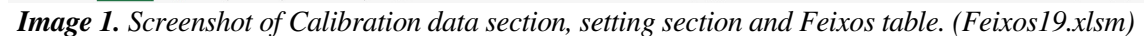
Furthermore, the programme includes a principal macro for calculation. Such macro is made of a set of functions for processing input information, calculating results and bringing out outputs to the main sheet “Feixos”.

7.3.1. “Feixos”

The “Feixos” sheet is subdivided in three main sections: Calibration data section “dades calibratge”, Setting section for input data “paràmetres” and results of calculated outputs “Feixos”. The user has to fill in all cells in yellow.

The first input in the Calibration data section is the date (*Cell B2*). The default value is the computer Operating System’s clock. However, the value might be manually changed. The format is dd/mm/yyyy. The second parameter is the calibration order code (*Cell B4*). This is an internal identification code to identify each instrument. The ambient temperature in °C and the pressure in hPa must be indicated in (*Cell B6 and Cell B7*).

In Setting section, the user must select the radiation quantity (*Cell C11*) from a list and introduce the table-center shift (*Cell D17*). When the radiation quantity is absorbed dose in tissue, the tissue thickness (*Cell E13*) must be specified. Next, the user must introduce the required dose rates, numerical values in (*Column A*) and the corresponding units (*Column B*) (See **Image 1**)



There is also another table “Taxa” where one can obtain the dose rate at a given distance and source in use. Results are plotted in columns E to F and I to J for integration mode (See Image 2).

Finally, if a new calibration has to be prepared, the data can be erased selecting “Esborrar contingut” button.

Image 2. Screenshot of Taxa table. (Feixos19.xlsm)

7.3.2. “Dades”

According to the requirements for the new programme, “Feixos19” should be designed to be easily updated when needed. The “Dades” sheet is intended to store all data used for the calculation. The sheet is divided in three sections: Beam equation section, Atmospheric Boundary Conditions section and Conversion Factor section.

Parameters of the equation are stored in the first section (*Cell B2-N8*). Each line corresponds to a different source number and the corresponding parameters A, B, MU, LD (defined in paragraph 5.3) for each part of the equation and the date of the beam calibration. The second section includes T,P correction factor that is automatically calculated but it might be modified (*Cell B10*), density of air (*Cell B12*) and distance factor that applies a correction of bench distance unit (*Cell B13*). The last block of data stores the conversion factors for each radiation quality, ^{60}Co and ^{137}Cs , respectively. The conversion factor units are indicated below (*Cell B16-F19*). The sheet is password protected so users are only allowed to apply changes in cells highlighted in orange.

	A	B	C	D	E	F	G
1	Font	A1	A2	MU1	MU2	B1	B2
2	1	1.748387	1.746347	0.00806	0.002342	-0.009625	
3	2	0.251406	0.253942	0.007587	0.003032	-0.000007	
4	3	0.91721	0.923109	0.008648	0.003816	-0.004246	
5	4	1.97591	1.988139	0.007329	0.00281	-0.007901	
6	5	2.868533	2.86054	0.0065185	0.006043	-0.01412	
7	6	9.482172	9.482172	0.007522	0.007522	-0.009661	
8	7	23.48659	23.48659	0.027096	0.027096	6.703152	
9							
10	Factor temp./Press. :	0.930626053					
11							
12	Densitat aire	1.293					
13	Factor_dist	0.01					
14					H*(10)	Hp(10)	
15	Exposició_conv	Dosi_absorbida_en_teixit	KERMA_aire_conv	Dosi_ambiental_equivalent_conv	Dosi_personal_equivalent_conv		
16	Conv_Co60	0.997	1.004976	1	1.16	1.15	
17	Conv_Cs137	0.998	1.000994	1	1.2	1.21	
18							
19	Factor_canvi_uni	114.1	110.1	1	1	1	
20		uR/uGy	urad/uGy	uGy/uGy	uSv/uGy	uSv/uGy	
21							
22							
23							
24							
25							
26							
27							
28							
29							
30							
31							
32							

Image 3. Screenshot of “Dades” sheet. (Feixos19.xlsm)

7.3.3. “Llistes”

This sheet stores all lists in use at “Feixos” sheet:

- List of radiological quantities and corresponding units for rate values.
- List of radiological quantities and corresponding units for integrated values.
- Source number option from 1 to 2.
- Radiation quality.

One of the most important characteristics of this sheet is the specific order of the information. Column G contains the correction factor for the selected unit, considering as a reference micro (μ) (see Image 4).

A	B	C	D	E	F	G
1 Magnituds operacionals:	Exposició	Dosi_absorbida_en_teixit	KERMA_aire	Dosi_equivalent_ambiental	Dosi_equivalent_personal	Factor_unita
2	R/h	rad/h	Gy/h	Sv/h	Sv/h	0.000001
3	mR/h	mrad/h	mGy/h	mSv/h	mSv/h	0.001
4	μ R/h	μ rad/h	μ Gy/h	μ Sv/h	μ Sv/h	1
5	nR/h	nrad/h	nGy/h	nSv/h	nSv/h	1000
6 Magnituds operacionals nom	Taxa d'exposició	Taxa de dosi absorbida en teixit	Taxa de kerma aire	Taxa de dosi equivalent ambiental	Taxa de dosi equivalent personal	-
7 Unitat integrada	R	rad	Gy	Sv	Sv	0.000001
8	mR	mrad	mGy	mSv	mSv	0.001
9	μ R	μ rad	μ Gy	μ Sv	μ Sv	1
10	nR	nrad	nGy	nSv	nSv	1000
11 Integrada	Exposició integrada	absorbida_en_teixit_integ	KERMA_aire_integrada	Dosi_equivalent_ambiental_integrada	Dosi_equivalent_personal_integrada	
12	Detector					
13	Obert					
14	Tancat					
15						
16 Fonts	Isòtop					
17	1 S-Co					
18	2 S-Cs					
19	3					
20	4					
21	5					
22	6					
23	7					
24						
25						
26						
27						
28						
29						
30						
31						
32						

Image 4. Screenshot of “Llistes”. (Feixos19.xlsm)

7.3.4. “Càlcul”

This sheet is divided in two main sections. The first section is intended to set the limit air kerma range of each source. The second section is used to copy all useful data from “Feixos” sheet and to store calculations.

“Càlcul” sheet uses the conversion factors from “Dades” sheet to transform the required radiation quantity into the corresponding air kerma rate whose base unit for calculation is μ Gy/s. Then it compares such values with the limits of every source and copies the corresponding data beam equation in use on the second section of “Càlcul” sheet. Once the macro “Ejecutar_calculo” is run (See 7.3.6 Macro “Ejecutar_calculo”), the results are stored in specific cells on the second section.

7.3.5. The new algorithm method

Paragraph 6.3.6 introduced the algorithm method of “Feixos99” to figure out the distance applying a constant step iteration approximation (Δp). The problem of this method is that Δp does not change if D_p^{i+1} does not go across the target distance, so it increases the calculation time in the iteration algorithm because it maintains the same step value during almost all the approximation.

Imagine that the algorithm is applied in the range between 1 and 3 meters for the first equation of ^{60}Co and the target distance is at 2.655 meters. According to lines 800 up to 945 within Feixos99 code: D_p , K , air kerma at D_p (K_{DP}) and target air kerma (K_T) will have the following values until the final result is obtained:

Nº iteration	k	D_p [m]	K_{DP} [mGy/h]	K_T [mGy/h]	$K_T - K_{DP}$ [mGy/h]	Δp $(-1)^k \cdot 10^{(1-k)}$
1	1	2	8.84228	4.98718	0.77302	-1
2	2	2.5	8.01277	4.98718	0.60667	+0.1
3	2	2.2	7.29414	4.98718	0.46258	+0.1
4	2	2.3	6.66748	4.98718	0.33692	+0.1
5	2	2.4	6.11778	4.98718	0.22670	+0.1
6	2	2.5	5.63294	4.98718	0.12948	+0.1
7	2	2.6	5.20317	4.98718	0.04331	+0.1
8	2	2.7	4.82044	4.98718	0.03343	+0.1
9	3	2.69	4.85679	4.98718	0.02614	-0.01
10	3	2.68	4.89355	4.98718	0.01877	-0.01
11	3	2.67	4.93073	4.98718	0.01132	-0.01
12	3	2.66	4.96833	4.98718	0.00378	-0.01
13	3	2.65	5.00636	4.98718	0.00386	-0.01
14	4	2.651	5.00254	4.98718	0.00308	+0.001
15	4	2.652	4.99872	4.98718	0.00231	+0.001
16	4	2.653	4.99491	4.98718	0.00155	+0.001
18	4	2.654	4.9911	4.98718	0.00079	+0.001
19	4	2.655	4.98729	4.98718	0.00002	+0.001

Table 19. Result of the constant step iteration approximation at 01/01/2019 with 20°C and 1013.25 hPa. (Feixos99.bas)

In that example, the final result is obtained after 19 iteration. This amount of iteration may cost unnecessary CPU time. To reduce the time of calculation the bisection method is implemented on Feixos19.

The bisection method considers a nonlinear equation defined as $f(x^i) = 0$ within a defined range $[a,b]$, where $f(a)$ and $f(b)$ have opposite signs ($f(a) \cdot f(b) < 0$). In our case, the function is defined as the difference between the required air kerma rate (K_T) and the fitted air kerma rate (K_{DP}):

$$f(x) = K_{DP} - K_T \quad (15)$$

This function is assumed to be continuous. The function is calculated at point x^i , middle point in the range $[a,b]$:

$$x^i = \frac{a + b}{2} \quad (16)$$

If $f(x^i) \neq 0$, a next iteration is performed for $[a, x^{i+1}]$ or $[x^{i+1}, b]$ selecting the new range in which the function changes of sign $f(a) \cdot f(x^{i+1}) < 0$ or $f(x^{i+1}) \cdot f(b) < 0$. (Schiavi, 2013) The method consists of repeatedly bisecting the interval defined by the range limits and then selecting the subinterval in which the function changes of sign.

Every repetition departs from the range of the previous iteration i . The distance x^{i+1} and the air kerma rate at this point will be respectively stored as D_p^i and K_{DP}^i in the new code. The calculation finishes when $|f(x^{i+1})| < Tolerance$. The tolerance is set to 0.0001, as it was in Feixos99.

The bisection method improvement is illustrated in the following table using the same boundary conditions as **Table 19**.

Nº iteration	Dp	K _{DP} [mGy/h]	K _T [mGy/h]	K _T – K _{DP} [mGy/h]
1	2	8.84228	4.98718	0.77300
2	2.5	5.63294	4.98718	0.12948
3	2.75	4.64460	4.98718	0.06869
4	2.625	5.10335	4.98718	0.02329
5	2.6875	4.86594	4.98718	0.02431
6	2.65625	4.98254	4.98718	0.00093
7	2.640625	5.04241	4.98718	0.01107
8	2.6484375	5.01234	4.98718	0.00505
9	2.65234375	4.99741	4.98718	0.00205
10	2.65429686	4.98997	4.98718	0.00056
11	2.65527344	4.98626	4.98718	0.00018
12	2.65478515	4.98811	4.98718	0.00017
13	2.65490723	4.98765	4.98718	0.00009

Table 20. Results of the bisection method iteration approximation. (Feixos19.xlsm)

The new method achieves the result with only 13 iterations. Consequently, it needs less computational time. However, this method has a weakness, because of the division over 2 in Equation (16), Dp is not limited by a 3rd decimal as it is in Feixos99, thus the uncertainty increases. To overcome this problem, x^i value is rounded to 3rd order. With this system, the two algorithms provide the same result.

The new code Feixos19 implements the bisection method with a 3rd order round-off as a new calculation algorithm.

7.3.6. Macro “Ejecutar_calculo”

All input data is used for calculation. “Ejecutar_calculo” is a macro that automates the different actions required to obtain the desired results. Macro “Ejecutar_calculo” is always run when the user inserts input data in “Feixos” sheet. This macro is made of different commands (See **Image 5**)

```

Sub Ejecutar_calculo(fila)
'Desproteger hojas
Call DesProteger_libro

Call DesProteger("Feixos")
Call DesProteger("Càlcul")

Preparacion_hojas (fila)

Boleano = Worksheets("Càlcul").Range(pos_booleano_calculo).Value

If Boleano = 0 Then
'No tiene nada que calcular
CommandButton_Click ("Càlcul no completat." + " Punt: " + CStr(fila - fil_primer_punto_hoja_feixos + 1))

ElseIf Boleano = 1 Then
'Calcula
Calcular (fila)

'Crea una tabla en la hoja Càlcul con las fuentes disponibles
Fuente_disponible (fila)

'Crea una lista para los diferentes puntos con su respectiva fuente y distancia
Crear_lista_resultados (fila)

'Los introduce en la hoja "feixos"
Introducir_lista_y_resultados (fila)

End If

'Proteger hojas
Call Proteger("Feixos")
Call Proteger("Càlcul")
Call Proteger_libro
Worksheets("Feixos").Cells(fila, col_puntos_hoja_feixos).Select
End Sub

```

Image 5. Screenshot of Sub “Ejecutar_calculo”. (Feixos19.xlsm)

The “Ejecutar_calculo” macro is structured in five main commands:

1. “Preparacion_hojas”: This function checks whether the input data is correct. If there is an abnormal input, a windows command reports an error. Otherwise, it deletes previous results of other calculation and copy the input data from “Feixos” to “Càlcul” sheet. If all performed actions pass successfully, it plots 1 in a cell called Boolean. This number is used for validating whether the input data is properly entered and allows to continue with the next commands. However, if there is an abnormal input, it will return a 0 and the calculation will stop until the input data is correct.
2. “Calcular”: It is the main function, it includes the calculation algorithm. First, it checks all sources that are available for being used in “Càlcul” sheet. It takes the corresponding air kerma rate, that was previously converted in “Càlcul” sheet, and runs the function “IteracionFont()”.

“IteracionFont()” is an inner function that calculates the distance for each available source through the bisection method. It loads all beam equation parameters such as A, B, MU, LD and range limits for each source.

Almost all sources are divided in two independent equations. Consequently, there exists an undefined gap between both equations. If the air kerma is in the gap, IteracionFont() returns 3 as a “recta” variable and extrapolates the 2nd equation for obtaining results. Subsequently, it loads the target value with the acceptance tolerance¹ for the calculation process and starts iterating.

The bisection method stops iterating when the target value is within the acceptance tolerance. At this point, IteracionFont() stores the results in specific cells. It saves the number of iterations made, the final range $[a, b]$ (See 7.3.5 *The new algorithm method*), the calculated value and the difference between the required air kerma rate and the calculated one.

3. “Fuente_disponible”: It plots the available sources in specific cells. This data is subsequently used for obtaining a source list.
4. “Crear_lista_resultado”: It creates a non-visual list that links every target value rate with its source, distance and calculated dose rate. It stores results in “Punt_X_dosi”, “Punt_X_distancia” and “Punt_X_font” lists for calculated dose rate, distance and available source, respectively. X is a number identification for each group of values. If the user requires several target dose rate values, the programme assigns a correlative identification number 1,2, 3 and so on. Those lists are used to complete “Feixos” sheet, later on.
5. “Introducir_lista_y_resultados”: It searches data from the previous lists and introduces them into the “Feixos” sheet. This function makes possible the interaction between the user and the interface of the programme for selecting results.

There is also the “CommandButton_Click” that is only a warning function. It notifies any malfunctioning of the programme to the user.

The complete code of “Feixos19” is shown in Appendix 8.

¹ The tolerance is previously defined by the assigned error that is stored in “Càlcul” sheet. (0.0001 by default)

8. Debugging and verification of “Feixos19”

This section describes the actions designed for the debugging and verification of “Feixos19” programme. Results are compared with “Feixos99”, subsequently analyzed and looked for either debugging errors or internal calculation failures.

8.1. Debugging and verification conditions

The first step has been to establish a protocol to verify the new programme “Feixos19”. A systematic set of conditions was defined to optimize and reduce time for the validation process. The optimization is based on performing a systematic analysis of the influence of the independent variables used in the calculations. These variables are called free variable.

8.1.1. Free variable

Free variables are a set of independent variables that have an important role in the execution of the programme and might modify the final results relying on operator’s requirements. The following free variables are considered:

1. Source number: Every source is included in the main iteration with different parameters of the equation. Thus, every equation should be taken into account for validating the correct input of the parameters of the equations.
2. Radiation quantity: Each radiation quantity has a unique conversion factor. This free variable is intended to validate the implementation of such factors.
3. Date: This variable is used to calculate the decay factor.
4. Temperature and pressure: It introduces changes on corrective attenuation factor.
5. Tissue thickness: It only affects the conversion factor for absorbed dose.
6. Bench distance: It changes the reference of distance source-measurement point with the table center shift distance.

8.2. Conditions

Based on the function of the variables listed in the previous paragraph and the relation between these variables, the verification protocol is set. The protocol establishes the reference and the test conditions for each free variable (See Table 21)

Free variable	Reference Condition	Test conditions
Source n°	2	1, 2, 3, 4, 5, 6 and 7
Radiation quantity	Air kerma	Air kerma, absorbed dose tissue, exposure, ambient dose equivalent and personal dose equivalent.
Tissue thickness	0 g/cm ²	0.007, 0.3 and 1 g/cm ²
Date	01/11/2018	01/11/2018 and 01/11/2000
Bench distance	0 cm	-10, 0 and 10 cm
Temperature and pressure	20°C and 1013.25 hPa	990 hPa and 15°C and 1020 hPa and 23°C

Table 21. Reference condition and Standard test condition for each free variable. (Prepared by the author)

The reference condition is selected while the corresponding free variable is not under test.

8.2.1. Verification of the beam equations

The verification of the parameters of the beam equations of each source is identified as condition A. Each source is defined as a free variable while the other variables are fixed in the reference condition.

Since two beam equations are used for most sources, the verification includes calculations for three points for each source: one point from the first equation, another point from the second equation and a third point corresponding to the intersection of the two equations. As a result, 20 different points are selected: 3 points for the first six sources and 2 points for source number 7, which is described with a single equation. The points to be tested are:

Source [n° \ mGy/h]	Highest limit	1 st points to be tested	Middle point	2 nd points to be tested	Lowest limit	3 th points to be tested
1	0.08730	0.05049	0.01368	0.01368	0.00201	0.00784
2	35.84204	19.87545	3.90885	3.90885	0.81883	2.36384
3	2.71328	1.50336	0.29344	0.29344	0.06145	0.17744
4	0.58537	0.32447	0.06356	0.06356	0.01336	0.03846
5	0.27857	0.15442	0.03027	0.03027	0.00541	0.01784
6	0.02527	0.01312	0.00097	0.00097	0.00049	0.00073
7	0.00075	0.00041	0.00006	0.00006	-	-

Table 22. Points to be tested for Condition A. (Prepared by the author)

8.2.2. Verification of the conversion factor

The verification of the conversion factor is identified as condition B. The aim of condition B is to verify the conversion factors used to determine the different radiation quantities. Ten points are selected: 5 for ^{60}Co and other 5 for ^{137}Cs . The reference conditions are as established in Table 21. The air kerma is set at 19.88 mGy/h which corresponds to source n°2 for point in the first range and a set at 0.05 mGy/h for source number 1 at the same distance. (See Table 23).

	Exposure	Absorbed dose in tissue	KERMA air	Ambient dose equivalent rate	Personal dose equivalent rate
Points to be tested for ^{137}Cs	2263.25 mR/h	2190.46 mrad/h	19.88 mGy/h	23.85 mSv/h	24.05 mSv/h
Points to be tested for ^{60}Co	5.74 mR/h	5.59 mrad/h	0.05 mGy/h	0.06 mSv/h	0.06 mSv/h

Table 23. Points to be tested for Condition B. (Prepared by the author)

8.2.3. Influence of tissue thickness

The influence of tissue thickness is identified as condition B'. The aim of condition B' is to verify that the free variable "tissue thickness" is well defined in the programme. In this case, absorbed dose rate must be selected as radiation quantity. Normally this quantity is used by few detectors with 7, 300 and 1000 mg/cm² of tissue thickness. Here three points are tested:

Tissue thickness [g/cm²]	0.007	0.3	1
Points to be tested [mrad/h]	2190.46	2190.46	2190.46

Table 24. Points to be tested for Condition B'. (Prepared by the author)

8.2.4. Influence of ambient conditions

The influence of ambient conditions is identified as condition C and has to verify that the correction of mass attenuation coefficient factor is correctly implemented. The verification is performed setting the most extreme ambient conditions (INTE, 2006) and keeping the other variables in the reference conditions. Source n° 2 and an air kerma rate of 19.88 mGy/h are considered. The condition C tests the following points:

Pressure [hPa]	990	1020
Temperature [°C]	15	23
Points to be tested [mGy/h]	19.88	19.88

Table 25. Points to be tested for Condition C. (Prepared by the author)

8.2.5. Influence of date

The influence of date is identified as condition D. The aim of condition D is to verify the influence of the decay factor. Two different dates are fixed at 01/11/2018 and 01/11/2000. The other variables are kept as before. Selected verification points are:

Date	01/11/2018	01/11/2000
Points to be tested [mGy/h]	19.88	19.88

Table 26. Points to be tested for Condition D. (Prepared by the author)

8.2.6. Verification of bench distance

The verification of bench distance is identified as condition E and is tested with -10 cm and 10 cm of table center shift.

Table center shift [cm]	-10	10
Points to be tested [mGy/h]	19.88	19.88

Table 27. Points to be tested for Condition E. (Prepared by the author)

8.2.7. Verification of “integrate” mode

This part includes the verification of the integrate mode and is identified as condition F. The aim of condition F is to verify that the integrate mode of Feixos19 is properly implemented. The rest of variable are set as the reference conditions. The integrate mode is only implemented with a simple division, so 2 different points values of air kerma are sufficient for the verification. An integration time of 6 min and 9 min are checked:

Integration rate [mGy]	1.5966	3
Points to be tested [mGy/h]	19.88	19.88

Table 28. Points to be tested for Condition F. (Prepared by the author)

8.3. Results

The criteria set for the analysis of results is based on the tolerance of the programme, considering its purpose. Results are acceptable if the relative difference of the radiation quantities is below 1% and the distance difference is below 1 mm. The relative difference is defined as the ratio between results reported by Feixos19 over the ones from Feixos99. The criteria are summarized as:

$$\left| 1 - \frac{Results_{Feixos19}}{Results_{Feixos99}} \right| < 1 \% \quad (17)$$

$$|Distance_{Feixos19} - Distance_{Feixos99}| < 1 \text{ mm} \quad (18)$$

Such criteria must be fulfilled for all conditions presented before a successful validation.

All results fulfill the acceptance criteria with a divergence below 1% and 1 mm at each condition. Both versions match their results, so conversion factors, tissue thickness variable, correction of mass attenuation coefficient factor, influence of decay factor, the integration mode and the bench distance factor are properly implemented in Feixos19. The details of the verification comparison are reported in appendix 9.

9. Conclusions

The main goal settled at the beginning of the project has been achieved. The objective of this project was to implement a new software that would allow to define the experimental conditions to calibrate radiation protection monitors or to irradiate passive dosimeters with gamma beams in the Secondary Standard Calibration Laboratory (LCD) at the Institut de Tècniques Energètiques (INTE) of the Universitat Politècnica de Catalunya (UPC).

Feixos19 does not only join features of the former programmes Feixos99 and Taxa 99 but it introduces new improvements such as the new interface that upgrade the user-friendliness, the enhancement for introducing new data parameters without modifying the code, the new improved calculation algorithm based on the bisection approximation method for a nonlinear equation and the integration of the new programme to the rest of the management system in place at the LCD. All those features have been put into effect thanks to the new implementation with the excel file.

The new programme has also been validated to test that all functioning of the former programme are completely fulfilled on Feixos19 and to check any other coding error introduced by the programmer.

A calibration of the gamma beam for source nº 2 has been also included in this project. This calibration has updated the data of the equation of the gamma beam from source nº 2 through a calibration session performed at 29/11/2018. The results have fulfilled the expected behavior as it is shown in appendix 5.

This project has bright future ahead with lots of possibilities to keep improving. In my opinion the next step would be implementing a new printing function in order to digitize the current procedures of the Second Calibration Laboratory.

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